Lightweight Concrete Using Pumice Stone – A State-of-the-Art Review

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Abstract
Lightweight concrete (LWC) has emerged as a promising alternative to conventional concrete, offering advantages such as reduced dead load, thermal insulation, fire resistance, and improved seismic performance. Among lightweight aggregates, pumice stone—a natural volcanic rock with high porosity and low density—has received increasing attention for producing sustainable LWC. This review systematically examines the use of pumice stone in concrete, with emphasis on fresh and hardened properties, durability, structural applications, and recent advancements involving admixtures and AI-based predictive modeling. The paper highlights that pumice-based concrete can achieve densities between 1500–2000 kg/m³ and compressive strengths ranging from 17–30 MPa, making it suitable for structural-grade applications. Challenges include reduced workability and water absorption, which can be mitigated by admixtures and pre-treatment of pumice aggregates. Finally, research gaps are identified in durability, life cycle assessment, and integration with modern technologies such as 3D printing and machine learning.

Introduction

Concrete accounts for over 8% of global CO_2 emissions, making the search for lightweight and sustainable alternatives critical. Lightweight concrete (density < 2000 kg/m³) reduces structural dead loads, enhances energy efficiency, and improves seismic resilience. Pumice stone, a natural lightweight volcanic aggregate, is widely available in regions such as India, Turkey, and Indonesia. Its porous structure and low specific gravity make it ideal for lightweight construction.

This review compiles findings from the past two decades on the mechanical, physical, and durability characteristics of pumice-based LWC, with a focus on practical applications and future research needs. Below are selected experimental and review studies that are often cited in the pumice-LWC literature (annotated): Kılıç, Atis & co. — 2003 — early structural LWC work: showed pumice-based mixes with fly ash can achieve structural-grade compressive strengths while reducing unit weight significantly. Ergül Yasar, Atis, Kilic 2003 Strength properties of LWC with basaltic pumice and fly ash; demonstrated feasibility of SLWC. Demirboğa (2007 / related years) effects of pumice ratio, cement dosage and slump on thermal conductivity and density; highlighted thermal benefits. Samimi et al. 2017 influence of pumice and zeolite on compressive strength and chloride resistance SCMs enhance durability. Tran et al. 2020 evaluated compressive strength and chloride-induced durability for pumice concretes; emphasised need for durability treatment. Lehner et al. 2021 numerical modelling and durability parameter variation for pumice mixtures (durability emphasis). Gündüz et al. 2023 studied rheoplastic pumice LWC with polymeric admixtures for pumpable mixes. Recent reviews (2023–2025) comprehensive reviews and meta-analyses synthesize developments, including use of pumice as SCM and LWC aggregate (Moolchandani 2025; ResearchGate advancements review 2025). The use for construction materials demand is increased due to infrastructure development worldwide. Natural coarse and fine aggregates are the main constituents of construction and building materials. Concrete is the material of choice for humanity because of its many uses, quick urbanization, and industrialization. Portland The three primary components of contemporary concrete—cement, coarse, and fine aggregate—each have a distinct role in the design of the concrete mix and are mostly produced using natural resources. Concrete is utilized extensively as a result of quick infrastructure and development, which degrades natural resources. As a result, researchers are now hoping to reduce the amount of natural coarse aggregates used in concrete by substituting them with other abundant natural aggregates, like pumice stone [4], either entirely [3] or in varied percentages [1,2].

A number of industrial wastes, including fly ash [6], wood ash [5], glass polishing power [7], wood fiber waste [8], rice husk ash [9], limestone powder [10], demolition materials [11], calcium carbonate residues [12], and ceramic powder wastes [13], have been used in recent and previous studies to replace cement in concrete. Nonetheless, some trash—such as rubber [17], recycled glass [15], plastic [16], and waste foundry sand [14]—are utilized as a natural substitute for fine aggregate. In addition, agro-waste [2], wood waste [19], recycled concrete aggregate and ceramic waste [18], and e-plastic waste [1] are utilized to replace pure grainy aggregate in the design of concrete mixes and to study the properties of concrete.

The literature also highlights lightweight aggregate pumice stone (PS) as a substitute for pure coarse aggregate in concrete, regardless of the waste materials and industrial by-product waste previously discussed. As a natural coarse aggregate substitute, PS is the subject of numerous studies worldwide to examine its strength characteristics, financial advantages, and environmental advantages. The economic benefits differ from one nation to the next. For example, a study on PS use in flexible pavement by M. Saltan and F. Selcan Fındık (2004) found that it costs $4,500 per unit length in Turkey [20]. Furthermore, additional researchers came to the conclusion that they ranged from $4 to $10, while natural stones typically cost between $10 and $15.

By effectively utilizing waste resources that are readily available in large quantities, PS can be used as a preferred alternative to natural coarse aggregate, offering both economic and environmental benefits [21]. Lightweight structural concrete is defined by ACI 213R-87, 1998 as having a density between 1350 and 1900 kg/m3 and a minimum strength of 17 MPa. The knowledge and application of high-strength, lightweight concrete based on artificial lightweight particles has grown significantly during the past 20 years [22–24]. A volcanic sponge-like material called pumice is created when magma suddenly freezes and traps millions of tiny air bubbles [25, 26].

On the outskirts of volcanic areas, pumice agate gates are common, particularly in the Mediterranean region, most of Indonesia and Turkey, and the US Rocky Mountains [27]. Nonetheless, small-scale studies have demonstrated that it is possible to create structural concrete with strength characteristics up to 25 MPa while still offering enough financial benefits [28–30]. According to Idi et al. and Sultan et al., pumice stones have a little lower compressive strength than regular concrete, which indicates that more materials are needed to maintain the compressive strength at a reduced weight [21,31].

Concrete containing PS can, however, reach 25 MPa strength and be utilized for structural reasons up to 50% replacement; after that, it can be used for non-structural applications. The benefits of using lightweight construction concrete with pumice stone for civil structural components include reduced total self-weight, fire resistance, reduced depletion of natural resources (economic benefits), and enhanced heat and sound insulation [23]. To assess the shrinkage (microcracks) in a mortar, some researchers substituted pumice stone for fine aggregate [32–35]. Liu et al. examine how the properties of the produced Ultra-High Performance Concrete (UHPC) are affected when pumices with different rates of water absorption are used to replace river sand by 10–30%.

They found that, while preserving engineering qualities, pre-wetting pumice (particle size distribution of 0.6–1.25 mm) may significantly reduce autogenous shrinkage of UHPC and enhance the interfacial transition zone (ITZ) skeleton between UHPC paste and hydrous pumice [36]. In order to assess the strength per performance, Karthika et al. employed pumice stone as a coarse aggregate in concrete at different replacement ratios. According to their findings, 50% pumice lightweight aggregate concrete (PLWAC) can be used to achieve the best CS, STS, and FS. It also lowers self-weight and absorbs more water because of its pores, which lowers the strength properties that can be utilized for partition walls, non-load bearing walls, and earthquake resistance structures [37].

Additionally, Zhang and Gjvorv use five various kinds of lightweight aggregates to examine the mechanical properties of high-strength lightweight concrete (HSLWC), concentrating on the strength controlling element. They came to the conclusion that HSLWC had a lower STS/CS ratio than HSNWC. The elastic modulus is significantly lower than HSNWC and ranges from 17.8 to 25.9 MPa [38]. By using pumice stone to partially replace coarse aggregate, T. Parhizkar et al. examined the structural cost, dead load reduction, foundation size, and reinforcement [39]. By replacing coarse aggregate (0%, 10%, 20%, 30%, 40%, and 50%) with a natural lightweight aggregate, pumice stone, B. Devi Pravallika and K. Venkateswara Rao suggested enhancing the durability and strength characteristics of M40 concrete [40].

The use of pumice stone as a partial aggregate substitute in cement concrete was studied by C. Krishnaveni and K. Guru Kesav Kumar [41]. In order to assess fresh, mechanical, and microstructural qualities, numerous research have been carried out on the replacement of waste, by-product, and natural resources over other readily available natural resources [42–48]. A group of scientific and computational techniques known as response surface modeling (RSM) are used to study how a physical system's response variable or variables interact with a number of external variables. The design expert program uses Central Composite Design (CCD) to plan and optimize the tests. The planned experiments are carried out following receipt of the mix design from the RSM-CCD.

The statistical model is constructed by using the experimental values as input parameters for linear regression. Strength characteristics including CS, STS, and FS were specified as response variables, whereas curing days and replacement percentage were employed as input factors. In recent investigations, a number of researchers optimized their experimental designs using RSM. For example, by substituting Ordinary Portland Cement (OPC) for geopolymer composite, Zahid et al. employed RSM to forecast the engineering features of the composite. To assess the strength characteristics, Ali et al. employed statistical modeling and concrete design that substitutes Waste Foundry Sand (WFS) for sand [49].

To assess the effect on semi-flexible payment, Khan et al. partially substituted OPC with silica fume and irradiated waste polyethylene terephthalate in different amounts [16,50]. Additionally, by employing heat-treated fly oil shale ash as an efficient additional cementitious material, Al Salaheen et al. used response surface methods to assess and optimize mortar compressive strength [51]. In their editorial, Fediuk and Ali compiled a number of papers that employed RSM for optimization, experimental design, and statistical analysis [52].

Memon et al. use RSM to examine the morphological, physicochemical, and rheological characteristics of petroleum sludge that contains bitumen [53]. The influence of natural coarse aggregate as a partial and complete replacement in concrete with PS must be examined in order to assess the mechanical and physical qualities of adding lightweight aggregate PS, according to contemporary and pertinent research. Optimization and statistical modeling of the concrete mixture have not been done, even though research publications on the substitution of PS for lightweight aggregate in regular concrete mixes are available.

By examining the mechanical and physical properties of lightweight aggregate PS as a coarse aggregate substitute in concrete utilizing the experimental design matrix made available by RSM's CCD function, the current work aims to close these gaps in the literature. Additionally, statistical tools (RSM) are made to optimize the design of concrete mixes and experiments. Finally, the PS and number of curing days for the best slump and mechanical properties were found using multi-objective design optimization based on pre-established design requirements. To confirm the best outcomes, more trials were carried out.

Pumice Stone as a Lightweight Aggregate

Physical and Chemical Characteristics

- **Bulk density:** 500–900 kg/m³
- **Water absorption:** 15–30%
- **Silica-rich composition:** Enhances pozzolanic activity when finely ground.
- **Porous microstructure:** Provides thermal insulation but reduces workability.

Global Availability

- Turkey and Iran are leading producers of pumice stone.
- In India, pumice deposits are reported in Rajasthan and Andhra Pradesh.

Fresh Properties of Pumice Concrete

- **Workability:** Decreases with higher pumice content due to high absorption.
- **Slump values:** Often reduced by 20–40% compared to normal concrete.
- **Solutions:** Use of superplasticizers, pre-soaking pumice aggregates, and partial blending with normal aggregates.

Hardened Properties

Density

- Normal concrete: ~2400 kg/m³.
- Pumice concrete: 1500–2000 kg/m³ (qualifies as structural lightweight concrete as per ASTM C330).

Compressive Strength

- **Range:** 17–30 MPa for mixes with 50–100% pumice replacement.
- **Applications:** High-rise buildings, prefabricated panels, seismic zones.

Tensile and Flexural Strength

- 15–25% lower than conventional concrete but acceptable for structural use.

Thermal and Acoustic Insulation

- Pumice concrete shows **30–50% lower thermal conductivity**, making it ideal for green building design.

Durability Characteristics

- **Chloride penetration:** Higher than normal concrete, but can be reduced with pozzolanic additives (fly ash, silica fume).
- **Freeze–thaw resistance:** Improved due to air voids.
- **Fire resistance:** Excellent performance due to porous structure.

Modern Advancements

Mineral and Chemical Admixtures

- Silica fume, fly ash, and GGBS enhance compressive strength and reduce permeability.

AI and Machine Learning in LWC

- Recent works use **Support Vector Machines (SVM), Random Forest, and SHAP analysis** for predicting UCS with high accuracy and interpretability.

3D Printing Applications

- Pumice-based mixes are being tested for **extrudability and printability** in construction **robotics.**

Research Gaps and Future Scope

Durability Studies: Long-term performance in marine and sulfate-rich environments is underexplored.

Life Cycle Assessment (LCA): Carbon footprint and energy analysis of pumice concrete.

Optimization with AI: More interpretable models (SHAP, LIME) should be integrated for mix design optimization.

Hybrid Mixes: Combining pumice with recycled aggregates and geopolymers for greener construction.

3D Printing: Exploring printability and reinforcement compatibility.

Conclusion

Pumice stone is a promising lightweight aggregate that reduces density by up to 30% while maintaining compressive strength suitable for structural applications. Its thermal insulation properties make it highly suitable for sustainable construction. However, challenges such as reduced workability and higher water absorption must be mitigated through admixtures, pre-treatment, or hybrid aggregate systems. With the integration of AI, durability studies, and green technologies, pumice-based lightweight concrete can play a significant role in future eco-friendly and cost-effective construction systems.

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